

Clouds and the Earth's Radiant Energy System (CERES)

Validation Plan

GEOLOCATE AND CALIBRATE EARTH RADIANCES INSTRUMENT

(SUBSYSTEM 1.0)

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CERES GEOLOCATE AND CALIBRATE EARTH RADIANCES LEVEL 1 INSTRUMENT VALIDATION PLAN

1.1 INTRODUCTION

This plan is designed to (1) trace the absolute calibrations of the CERES spacecraft sensors radiance and geometric measurements from ground to flight, (2) define short-term and long-term shifts or drifts in the measurements caused by sensor response variations, and (3) determine measurement consistency among the same types of CERES sensors on the same and different spacecraft platforms. The plan is described in detail by Lee *et al.* (1996a)

1.1.1 Measurement and Science Objectives

The CERES scanning thermistor bolometers will measure Earth-reflected and emitted filtered radiances in the broadband shortwave (0.3 μm - 5.0 μm), broadband total-wave (0.3 μm - >100 μm), and narrow-band water vapor window (8-12 μm) spectral regions. Broadband longwave radiances (5 μm - >100 μm) will be derived from the differences between the total-wave and shortwave radiances. These radiance measurements, along with imager measurements, are designed to define the impacts of clouds and of certain cloud properties upon the Earth's radiation budget and climate (Wielicki and Barkstrom 1991, Wielicki *et al.* 1996).

1.1.2 Missions

The CERES bolometers will be launched aboard the Tropical Rainfall Measuring Mission (TRMM) and Mission to Planet Earth (MTPE) Earth Observing System (EOS) spacecraft platforms. The TRMM spacecraft, carrying a CERES instrument package, is scheduled for a November 1, 1997 launch. The spacecraft will be placed into a low-inclination 35°, 350-km altitude orbit using a National Space Development Agency (NASDA) H-II expendable launch vehicle which will be launched from the Tanegashima Space Center, Japan. The EOS Morning (AM-1) and Evening (PM-1) spacecraft platforms, each carrying two CERES instrument packages, are scheduled for launches in June 1998 and December 2000, respectively. The EOS spacecraft platforms will be launched into Sun-synchronous polar, 705-km orbits using NASA Atlas IIC launch vehicles. During 2004, a sixth CERES instrument package is scheduled for launch on the follow-on TRMM-2 or EOS AM-2 platform.

1.1.3 Science Data Product

The CERES level 1 instrument data product is geolocated filtered broadband radiances, in $\text{Wm}^{-2}\text{sr}^{-1}$, at the top-of-the-atmosphere (~30 km). For average target scenes less than $100 \text{ Wm}^{-2}\text{sr}^{-1}$, the shortwave and longwave instrument measurement accuracies requirements are 0.8 and $0.6 \text{ Wm}^{-2}\text{sr}^{-1}$, respectively, as indicated in Table 1. Earlier Earth Radiation Budget Experiment (ERBE) spacecraft versions (Barkstrom 1984, Barkstrom and Smith 1986) of the CERES in-flight calibration systems have been used to verify shortwave and longwave radiance measurement precisions at the $\pm 0.3 \text{ Wm}^{-2}\text{sr}^{-1}$ uncertainty level (Lee *et al.* 1993). The scene radiances will be located geographically with estimated uncertainties of the order of 1 km near the nadir. During the ERBE spacecraft missions, validation studies verified the geolocation estimates

at the ± 6 km uncertainty level (Hoffmann *et al.* 1987). A similar geolocation validation technique will be used for the CERES measurements.

1.2 VALIDATION CRITERION

1.2.1 Overall approach

The CERES level 1 radiometric data product validation plan includes (1) assessments of the degree to which the absolute longwave and shortwave radiometric scales are transferred from the ground to space by the CERES sensors and in-flight calibration sources, (2) the in-flight long-term stabilities of the CERES sensor responses, (3), in the case of sensor response drifts or shifts, revisions to the sensor in-flight count conversion coefficients (gains and offsets), (4) validations of the geolocation calculations using observations of geometric registration sites, and (5) the accuracy and precision estimates of the geolocated filtered radiances. Ground-calibrated instrument count conversion coefficients are used to convert the sensor output signals into radiances. Ground coefficients, derived in the TRW Radiometric Calibration Facility (Lee *et al.* 1996b and Lee *et al.* 1997) and tied to absolute radiometric temperature-based scales, are the initial in-flight coefficients. In-flight coefficients will not be revised if the sensor response drifts or shifts less than the 0.5% level in the longwave spectral region or less than the 1% level in the shortwave region. If the sensor response drifts or shifts above these levels, then the flight coefficients will be revised off-line in science computing facilities (SCF) and applied only after approval by the CERES Science Team.

The elements of the overall validation plan for the level 1 geolocated filtered radiances include (a) in-flight calibration systems analyses (Lee *et al.* 1992, Lee *et al.* 1993); (b) geometric registration sites/coastline detection analyses (Hoffmann *et al.* 1987) to estimate upper limits in geolocation errors; and (c) single and multi-spacecraft intercomparisons of Earth radiance measurements from the same type of broadband sensors (Avis *et al.* 1994) in the cross-track and rotating azimuth plane (RAP) Earth radiance scanning modes.

The instrument validation success will be checked using multi-sensor intercomparisons of Earth radiance measurements from the same spacecraft (Green and Avis 1996). The CERES radiances are ground calibrated and monitored for drifts and shifts by in-flight calibration sources. These activities, may not guarantee that the CERES data are consistent with the historical ERBS data (Barkstrom 1984, Barkstrom and Smith 1986), or that the in-flight calibration systems are stable. For example, on ground the total channel is tested against the on-board blackbodies. In flight the same procedure is performed. If the two readings are different, it will not be clear whether the change is from the radiometer or the blackbody. The same is true for any detected drift. For these reasons the CERES radiances will be validated against Earth validation targets (Staylor 1986, 1993). The statistics of the radiance for these targets will be established with 5 years of validated ERBS scanner data (Green and Avis 1996). If statistically significant differences between the CERES measurements and the earth validation targets are found, and if these differences are consistent with the in-flight calibration systems results and are within the uncertainties of the instrument calibration and validation, then the radiances will be revised with the approval of the CERES Science Team. If the differences are outside the instrument uncertainties, then all analyses will be reexamined and additional sources of verification will be sought. It is probable that superior

CERES calibration systems and consistency between the CERES ground and in-flight calibration will make CERES the standard and assess possible biases in the ERBS data.

1.2.2 Sampling Requirements and Trade-offs

The operational in-flight coefficients will be evaluated and revised using in-flight calibrations and validation studies. During the first 30 days in orbit, the sensor contamination doors will be closed. During this period, the sensors will be calibrated daily using the internal calibration systems. After the doors are opened, in-flight calibrations will be performed daily during the first week of Earth radiance measurements, every other day during the second week, once a week for the third and fourth weeks, and thereafter every 14 days.

Validation measurements of the Earth radiances will be used to verify sensor response changes, indicated by in-flight calibrations. The CERES science team will conduct detailed analyses of the first 6 months of in-flight calibrations and the validations before the sensor gains or offsets are revised. Validation of the CERES radiances against earth validation targets will require a minimum of one month of data. Additional months will strengthen the statistical hypothesis tests and increase the probability of detecting errors if they exist. Thereafter, during the remainder of the mission, every 14 days, the in-flight calibrations and validation studies will be evaluated to detect short-term and long-term sensor relative responses changes more than 0.5% in the long-wave region or 1% in the shortwave region. The CERES sensors sampling rate of Earth radiances are sufficient to carry out planned validation studies.

1.2.3 Measures of Success

The CERES calibration/validation efforts will be partially successful if the CERES mean annual global unfiltered longwave radiances are approximately $77 \pm 2 \text{ Wm}^{-2}\text{sr}^{-1}$ over an integral number of spacecraft precession cycle. During the 1985-1986 period, the precessing Earth Radiation Budget Satellite (ERBS) and the polar-orbiting NOAA-9 spacecraft scanning narrow-field-of-view thermistor bolometer sensors yielded global mean Earth radiance values near $77 \text{ Wm}^{-2}\text{sr}^{-1}$. During the 1984-1997 period, Earth irradiance measurement trends from the ERBS nonscanning wide-field-of-view active-cavity radiometers indicate that the annual mean global Earth longwave radiances varied less than $2 \text{ Wm}^{-2}\text{sr}^{-1}$ from the $77 \text{ Wm}^{-2}\text{sr}^{-1}$ value during the 1984-1997 time frame. Shortwave radiances vary with the local solar time of the measurements. Therefore, for the shortwave radiances, the measures of success cannot be defined as precisely as the measures for the longwave radiances.

The measure of successful validation of the CERES radiances is statistical agreement between the instrument on-board validation plan and the empirical validation plan that there are no additional statistically significant adjustments to the radiances. In addition, it must be shown that any error large enough to invalidate the radiances would have been detected. This measure of validity and the mission accuracy goals will dictate how many months of data is required to reach this decision.

1.3 PRE-LAUNCH ALGORITHM TESTS/DEVELOPMENT ACTIVITIES

1.3.1 Field Experiments and Studies

Further studies are needed to insure that the ERBS total channel radiance at night, which is here being taken as the absolute reference, is statistically consistent with established data sets.

1.3.2 Operational surface Networks

N/A

1.3.3 Existing Satellite Data

2.3.3.1 Validation of the longwave response of the total channel - The longwave response of the total channel and the individual offsets for each distinct measurement position are validated by comparing data averages to an earth validation target with known radiance statistics. A good longwave validation target is all tropical ocean between $\pm 30^\circ$ latitude with any cloud condition. From 5 years of validated ERBS data, we know that a single radiance measurement over tropical ocean at a given viewing zenith angle varies by $\pm 15\%$ (one standard deviation) and the daily average of all measurements over the tropical ocean at the same viewing zenith varies by $\pm 1\%$. The monthly average varies by $\pm 0.5\%$. Thus, averaging 30 days of data only reduces the uncertainty from 1% to 0.5% and implies that daily averages are not independent. Monthly averages, however, seem to be nearly independent so that multiple monthly averages have an uncertainty that decreases as the square root of the number of months. Knowing the statistics of the Earth validation targets allows us to detect statistically significant errors in the longwave response of the total channel.

CERES radiances from the total channel at night will be averaged over the tropical ocean for a minimum of one month and the average radiance for each of the 225 measurement positions recorded. These data points should be statistically consistent with the same results from ERBS. In general, the data averages will not fall on the general limb-darkening curve for the target area as established by ERBS. We then hypothesize a single gain correction to the total channel data so the corrected data is a weighted least squares fit to the general limb-darkening curve where the weights are based on the limb-darkening curve variances. The gain change essentially changes the magnitude of the measurements until the data is clustered around the known general limb-darkening curve. If the gain change is statistically significant, then the longwave response is changed either with the spectral correction coefficients (Subsystem 2.0- ERBE-Like Inversion) or in the instrument equation (Section 1.3.1.4.3). If the gain change is not significant, the spectral correction coefficients are considered valid. In either case the offset corrections are determined by subtracting the general limb-darkening value from the corrected data value. Each offset is examined to determine if it is significant and changed accordingly. The above procedure can be used initially to validate the offsets and used throughout the mission to test the stability of the offsets.

The fitting of the longwave radiances of the total channel to the validation target values is not unique. For example the data could have been corrected with only offsets. In flight it is felt that the offsets will be known better than the gain. First, the offsets are determined in flight with a

pitch-up maneuver (Section 1.4.8) that scans space and establishes the zero-reference offset variations for each of the 225 distinct scanner positions relative to the space look position offset. The ERBS performed two pitch-up maneuvers to determine offsets and concluded that the offsets were constant and did not change over a year. As a result ERBS used one set of initial offsets for the entire 5 year mission. Another reason for changing the gain first and the offsets second is that offsets change the nature of the estimated flux field at the top-of-the-atmosphere. A gain change increases all flux proportionally and is a linear change. Offset changes on the other hand change the limb-darkening nature of the measured field so that fluxes derived from nadir views change differently than fluxes derived from limb views. The non-linear nature of offset changes becomes imbedded in the results. It seems only reasonable that when making a statistically significant change we would want to make as much of the change with gain and only then make offset changes.

All of the gain and offset changes to the total channel would be made only if they are within the statistically uncertainty of the in-flight calibration system and with the approval of the CERES Science Team.

1.3.3.2 Validation of the window channel - The window channel radiances are validated in the same way as the longwave radiances of the total channel (Section 1.3.3.1). The only difference is the addition of a narrowband to broadband conversion which will increase the uncertainty in the statistical tests.

1.3.3.3 Validation of the shortwave channel and the shortwave part of the total channel - The shortwave channel is validated by a three channel intercomparison test (Green and Avis 1996) and shortwave Earth validation targets. The three channel test is based on the redundancy between the shortwave, total, and window channel measurements. Since shortwave radiances are highly variable, it is advantageous to examine daytime longwave differences and infer shortwave differences.

The shortwave validations test only the instrument gains. Recall that the total and window channel offsets are validated at night (1.3.3.1, 1.3.3.2). In addition the shortwave offsets are set with a zero reference at night (Section 1.4.8). Therefore, only gain changes are appropriate for the shortwave channel.

The first step of intercomparing the three channels is to regress the window channel against the validated total channel at night for all 12 ERBS scene types. Having matched the window radiances to the longwave radiances of the total radiances, we use the window channel to transfer our longwave standard from nighttime to daytime. We determine the daytime longwave radiances from the window channel and also determine the longwave radiances by the normal approach of subtracting the shortwave from the total channel radiances. These two estimates of broadband longwave radiance should agree on average. Recall that the longwave portion of the total channel radiances has been validated and the window radiances matched to the total at night. Only shortwave errors would cause the two longwave measurements to differ on average. Thus, if there is a significant difference between the longwave radiances and those from the matched window channel and the total minus shortwave channel, then either the shortwave channel is in error, or the shortwave part of the total channel is in error, or both are in error. We cannot determine where the shortwave error source is located from the three channel intercomparison test.

Next, we examine shortwave Earth validation targets with known statistics from validated ERBS data. A likely target area is the desert area known as the Arabian Empty Quarter within the Saudi Desert. This area is almost entirely sand dunes and sand seas, and the lack of moisture and the saline nature of the sand cause it to be virtually free of all vegetation (Staylor 1986). As a result this area is uniform in shortwave. We then compare the shortwave channel measurements against the shortwave validation target and test for statistically significant differences. We can also test the shortwave portion of the total channel against these targets by subtracting the matched window channel from the total channel. These tests will be used to proportion the shortwave gain change as inferred from the three channel Intercomparison test between the two potential shortwave error sources.

Suppose a gain change was previously made to the total channel (1.3.3.1). If it was made in the instrument equation, then it will also affect the shortwave portion of the total channel. If the gain change is made by changing the spectral response function of the total channel in the longwave part only and recalculating the spectral correction coefficients, then the shortwave portion of the total channel is unaffected. A change in the instrument gain (A_V , see Section 1.3.1.4.3, eqn 1-1) to correct longwave portion of the total channel and a compensating gain change in shortwave portion of the total channel would signal that the longwave portion of the total channel should be changed with the spectral correction coefficients and not A_V .

As a final validation of the offsets, we can regress the longwave differences from the three channel intercomparison test on the shortwave radiance. We would expect no significant intercept since the offsets have been validated. If we find a significant intercept, then part of the computed gain change is an offset change and the offset validation must be reexamined.

All of the gain changes to the shortwave channel and the shortwave portion of the total channel should be made only if they are within the statistically uncertainty of the in-flight calibration system and with the approval of the CERES Science Team.

1.3.4 In-flight Calibration Systems

The ground derived count conversion coefficients will be used as the preliminary flight sensor count conversion coefficients (gains and offsets). Using built-in flight calibration systems, sensor calibrations are conducted during the ground derivation of the coefficients; during the thermal-vacuum testing of the sensors on the spacecraft, prior to launch; and shortly after launch. Analyses of the ground to launch flight calibration measurements will be used to define the degree to which the sensor and flight calibration systems transferred the longwave and shortwave absolute radiometric scales into orbit. After launch, time series of the in-flight calibrations will be used to determine revisions to the initial in-flight coefficients, along with analyses of validation plan elements.

1.3.4.1 - CERES Instrument Package - Each CERES instrument package consists of a scanning thermistor bolometer sensor assembly (Lee *et al.* 1996b), elevation axis drive system, azimuth axis drive system, pedestal, and associated electronics as shown in Fig. 1. The CERES instruments are being designed, manufactured, and tested by TRW's Space and Electronics Group,

Spacecraft and Technology Division (Redondo Beach, CA) under NASA contract NAS1-19039. Each sensor assembly has three detector units. One is a broadband shortwave unit which measures Earth-reflected solar radiances in the 0.3 μm to 5.0 μm spectral region. The second sensor unit is a total-wave broadband radiometer which measures both Earth-reflected and Earth-emitted radiances in the 0.3 μm to >100 μm spectral region. The third one is a narrow-band unit which measures Earth-emitted longwave radiances in the 8 μm to 12 μm spectral region. The three sensors are co-aligned and mounted on a spindle that scans about the elevation axis (See Figs. 1 and 2). The sensor assembly elevation pointing can be resolved at the 0.005 degree level using 16 bit optical position encoders. The sensors fields' of view overlap by at least 98%. The sensors and elevation axis drive system can rotate about the azimuth axis at rates between 4 and 6 angular degrees per second of time. The azimuthal pointing can be resolved at the 0.005 degree level using position encoders. Once every 10 milliseconds, the averaged elevation and azimuth positions are sampled and recorded. The mass of each instrument package is less than 45 kg. When the azimuth drive is stationary and when the sensor scans in the elevation plane (cross track mode), each instrument package uses less than 41 Watts of electrical power. Each instrument uses less than 47 Watts in the biaxial mode, in which the instrument is both scanning in the elevation plane and rotating in the azimuthal plane (rotating azimuth plane mode). The instrument package can be contained in a cube, 60 cm in height.

The Earth radiance measurements will be collected in the normal or short science scan cycle. All science and calibration scan cycles are 6.6 seconds in duration in which the sensors output signals are sampled every 10 milliseconds while housekeeping data are sampled, at least once. In Fig.2, a cross-sectional view of the CERES instrument is presented for the elevation plane. For the TRMM orbital configuration, the normal scan cycle includes observations of cold space [near zero radiance source at a temperature of 2.7 K (Turner 1993)] at the elevation angle of 11 degrees, of the Earth between 19 and 161 degrees, a second look at cold space on the other side of the Earth at 169 degrees, and of the built-in internal calibration module (ICM) system at 194 degrees. For the EOS orbit, cold space is observed at the elevation angles of 18 and 162 degrees while the Earth is observed between 26 and 154 degrees. During normal science cycle, the internal calibration sources are not activated. As shown in Fig. 2, in the short scan, the sensors observe cold space at 11 degrees, and Earth between 19 and 141 degrees. During short scans, observations are not conducted of the cold space at 169 degrees and of the calibration system at 194 degrees. The short scan will be used primarily during the rotating azimuth plane (RAP) operations to prevent the sensors from staring at the Sun and the solar observations altering the sensors' responses. The short scan restricts the scanning sensors to elevation angles below the Earth limb on the Sun side.

The first cold space observations, at the elevation angle of 11 degrees, are used in the data reduction process for each 6.6 second scan cycle. The set of space observations, at 169 degrees, are not used in the data processing because they are not available during the short scans.

The cross-track mode is the most important operational science measurement configuration in which the azimuth position is fixed. The sensors operate in normal or short scan cycles in a whiskbroom pattern perpendicular to the orbital plane. The cross-track measurements are the primary data used by the CERES science team for performing Earth radiation budget studies.

The rotating azimuth plane (RAP) mode is an operation in which the azimuth axis is rotated at a constant rate of 6 angular degrees per second in one direction for 30 seconds and then it is rotated in the opposite direction at the constant 6 degrees per second rate for the next 30 seconds. A complete azimuth scan cycle is completed in 1 minute. In the RAP mode, the elevation plane of the sensors oscillates through an azimuth angle of 180°. The short scan cycle is used to avoid possible observations of the Sun near the sunrise or sunset positions. During the RAP operations, the sensors can measure radiances from geographical scenes with varying incident solar radiation and observing geometry. The RAP data will be used to compute new angular distribution models for converting sensor radiances into irradiances at the top of the atmosphere.

For the TRMM mission, the single instrument package will operate in the cross-track and RAP modes about 67% and 33% of the time, respectively. During the EOS AM-1 and PM-1 missions, there will be two instrument packages. One will be operated continuously in the RAP mode while the other instrument will be operated in the cross-track mode.

1.3.4.2 Sensor Unit - Each sensor unit consists of a telescope baffle, Cassegrainian telescope, and thermistor bolometer detector module. The unit is 9.2 cm in length. The telescope baffle prevents energy from striking the active bolometer flake at angles greater than 16° off of the telescope optical axis. The f/1.8 Cassegrainian telescope module has an 18-mm diameter silvered primary mirror and a silvered secondary mirror. In the shortwave and in the water vapor window sensor units, filters are located in two places: before the secondary mirror spider and in front of the active bolometer flake. The 8 µm to 12 µm window filter system consists of a 1-mm thick zinc sulfide and a 0.5-mm thick cadmium telluride filter element. Each shortwave filter is a 1-mm thick fused, waterless quartz element. The total-wave sensor unit does not have an optical filter.

The detector module has an active and a reference thermistor bolometer flake with time constants less than 9 and 12 milliseconds, respectively. The TRMM (proto-flight model) shortwave, total-wave, and window active flakes have time constants of 8.7, 7.9, and 8.2 milliseconds. In the detector module, the active and the reference flakes are mounted on separate disk assemblies which are in thermal contact with each other and with the heatsink which is maintained at a constant temperature of 38° Celsius using a 2.3-Watt electrical heater. The active and reference flakes are covered with 12-µm thick absorptive black paint layers of Aeroglaze Z-306 doped with 10% carbon black. The absorptance of the paint layer is greater than 85% out to 100 mm (Jarecke *et al.* 1991).

1.3.4.3 Flight Algorithms - The CERES data reduction algorithms follow the procedures developed for the NASA Earth Radiation Budget Experiment (ERBE) to preserve continuity with the ERBE long-term data sets. The filtered radiance measured by each sensor unit can be expressed by following algorithm (Halyo *et al.* 1989, Lee *et al.* 1989, Lee *et al.* 1996b).

$$\begin{aligned} \tilde{L}(t - \tau) = & A_V[m(t) - \bar{m}(t_k) - o(t)] + \frac{t - t_k}{\Delta t}[A_S(\bar{m}(t_{k+1}) - \bar{m}(t_k)) \\ & + A_H(T_H(t_{k+1}) - T_H(t_k)) + A_D(V_D(t_{k+1}) - V_D(t_k)) \\ & + A_B(V_{bias}(t_{k+1}) - V_{bias}(t_k))] \end{aligned} \quad (1)$$

where

$$t_k = t_{k-1} + \Delta t$$

and $m(t)$ = instrument output (digital counts) sample at time t , $\bar{m}(t_k)$ is the averaged instrument output in digital counts when viewing cold space at t_k at the beginning of every 6.6 second scan, and $o(t)$ is the sensor zero-radiance offset variation with elevation angle/geometry. The other terms and constants are defined as

$T_H(t_k)$ = heat sink temperature measurement (K) at t or most recent time

Δt = total scan period of 6.6 seconds.

t_k = time at end of space look (sec.)

t = sampling instant (sec.)

$V_{bias}(t)$ = sensor bridge bias voltage measurement at time t or most recent value, counts

$V_D(t_k)$ = drift balance digital to analog converter (DAC) voltage measurement at time t or most recent value, counts

τ = average time lag between the instantaneous detector optical field of view and point spread function centroid (sec.).

C = digital to analog conversion factor, 409.5 digital counts/volt

while the coefficient gain terms A_V , A_S , A_H , A_D , and A_B are defined as:

$$A_V = \frac{AV}{CV_{bias}(t)} \quad (2)$$

$$A_S = \frac{AVA}{CV_{bias}(t)} \quad (3)$$

$$A_H = \frac{AHA}{CV_{bias}(t)} \quad (4)$$

$$A_D = \frac{AD}{CV_{bias}(t)} \quad (5)$$

$$A_B = \frac{AB}{CV_{bias}(t)} \quad (6)$$

where AV , AVA , AHA , AD , and AB are constants determined using the ground calibration data (Lee *et al.* 1996b; Jarecke *et al.* 1993).

The housekeeping data $T_H(t_k)$ and $V_D(t_k)$ are transmitted to Earth once every scan and are not available for every instrument output sample during the scan. The coefficient gain terms A_V and A_H are determined using the sensor voltage and heat sink temperature measurements, respectively. The sensor gain term, A_V , in (1) is the most important gain term. It is important to point out that the A_H , A_D , and A_B terms in CERES thermistor bolometer ground calibration data analyses were found to be negligible and set equal to zero.

1.3.4.4 In-Flight Calibration Systems - The internal calibration module (ICM) and the mirror mosaic attenuator (MAM) are the two in-flight systems which are built into the CERES instrument package and are used to define shifts or drifts in the sensor responses. The location of the in-flight calibration systems are shown in Fig. 2, at the elevation angle of 194 degrees. The primary in-flight calibration system is called the internal calibration module (ICM). The ICM and the sensors will carry the ground calibration radiometric scale into orbit. As shown in Fig. 3, The ICM consists of 2.75-cm diameter, concentric grooved, anodized black aluminum blackbody sources for the total and window sensors, and an evacuated tungsten lamp source, known as the shortwave internal calibration source (SWICS), for the shortwave sensor. The CERES SWICS operates at 4 constant specific radiance levels, including off, between 0 and $400 \text{ Wm}^{-2}\text{sr}^{-1}$. ICM's were used to calibrate thermistor bolometers and active-cavity radiometers aboard the Earth Radiation Budget Satellite (ERBS), NOAA-9, and NOAA-10 spacecraft platforms. The ERBE SWICS's operated at levels near of 0, 90, 160, and $270 \text{ Wm}^{-2}\text{sr}^{-1}$. The first non-zero level of SWICS tungsten lamp has peak radiances near $1.7 \mu\text{m}$, since it operates at temperatures near 1700 K.

In ground vacuum facilities, the CERES blackbodies were operated and maintained at several temperatures between ambient and 320 K. Imbedded in the blackbodies, platinum resistance thermometers (PRT) indicate the temperatures of the blackbodies' emitting surfaces. Before the PRT's are placed in the ICM blackbody structure, the PRT's are calibrated in a temperature controlled bath to verify that the correct coefficients are used in the PRT temperature equation at 273.16 K. The blackbody radiances are calculated from the Stefan-Boltzman relationship using the PRT temperatures and the effective blackbody emittances. Using (1) above, the total-wave and window sensors measurements of the in-flight blackbodies are converted into filtered radiances. The calculated sensor and the calculated blackbody radiances are compared using regression analyses to verify that the blackbodies were on the same radiometric scale as the sensors. In orbit, the ERBE in-flight blackbodies operated from ambient temperature (291 K thru 303 K) to 20 degrees above ambient. The CERES blackbodies will be operated in a similar manner up to 326 K. The ICM calibrations are performed when the sensors operate in the normal scan cycle. The SWICS is not operated at the same time that the blackbodies are heated actively.

In Fig. 4, the ERBS ICM flight calibration measurements demonstrate that the ERBS sensor bolometers and their calibration sources were stable within 0.3% over a 5-year period (Lee and Barkstrom 1991, Lee *et al.* 1993). The measurements represent changes in the averaged differences between bolometric observations of space and of either the ICM activated shortwave lamp or blackbody. The measurement dropouts were caused by misalignment between the bolometers and the calibration sources. The misalignment occurred when the sensor scanning mechanism became sluggish (Kopia and Lee 1992). The ERBS flight calibration measurements demonstrate the maturity of the CERES ICM design.

In Fig. 2 and at an elevation angle of 236 degrees, the second in-flight calibration system is called the mirror attenuator mosaic (MAM), a solar diffuser plate. The MAM is used to calibrate each the shortwave and total-wave channels using the solar radiances reflected from the MAM's. Each MAM consists of baffle-solar diffuser plate systems which guide incoming solar radiances into the instrument fields of view of the shortwave and total wave sensor units. The MAM baffle, solar view cover, and MAM are labeled in the Fig 1. The MAM diffuser plate consists of an array of spherical aluminum mirror segments which are separated by a black paint reflecting surface. Thermistors are located in each MAM plate and in each MAM baffle. The CERES MAM design is expected to yield measurement precisions approaching 1% (Folkman *et al.* 1993). The basic ERBE MAM calibration approach, flight data reduction algorithms, and in-flight performance have yielded measurement precisions at the 3% level (Lee *et al.* 1992). The ERBE MAM results demonstrate the maturity and reliability of the MAM calibration system. In the following paragraph, the CERES basic solar calibration approaches are described. They are similar to those used for ERBE.

The MAM calibration procedure includes measurements of the MAM before the Sun drifts into the MAM baffle field of view, of the MAM when the Sun is in the field of view, and after the Sun has drifted out of the view. During the MAM scan cycle of 6.6 seconds, the sensors make staring radiance measurements of first the MAM, second the ICM, and then cold space at the elevation angle of 169 degrees. The ICM is not activated during the MAM calibrations.

The total-wave and shortwave sensors are used to measure the MAM-reflected shortwave and longwave radiances as well as MAM emitted longwave radiances. For the shortwave sensor, the MAM-reflected shortwave radiances are equal to the differences between the MAM and cold space reference radiances. In the case of the total-wave sensor, the MAM radiances consist of both shortwave and longwave components. Therefore, for the total-wave sensor calibrations, the MAM-emitted and -reflected longwave radiances must be regressed against the MAM baffle and MAM structure temperatures in order to derive an empirical relation for the MAM longwave radiances as a function of MAM temperatures. The empirical relationship is used to define the longwave component of the mixed shortwave and longwave radiances from the MAM during flight calibrations.

The MAM is a relative calibration system. Its vectorial reflectances are not defined absolutely or spectrally. The ERBE MAM reflectances varied systematically with varying incidence angle as much as 20%. The CERES MAM is designed to reduce the reflectance variations. Laboratory testing of the CERES Proto-Flight Model MAM's indicates systematic reflectance variations less than $\pm 2.5\%$.

1.4 POST-LAUNCH ACTIVITIES

The sensors' flight gains and offsets will be evaluated using in-flight calibrations and validation studies. The pre-flight laboratory-derived sensor gains and offsets (Lee *et al.* 1997) will be used as the initial flight count conversion coefficients to convert the CERES sensor output signals into radiances. The time series of ground to early orbit ICM measurements will define the degree to which the sensors and ICM maintained the ground absolute calibrations and the initial ground to flight corrections to the flight coefficients. In-flight ICM and MAM calibrations will be used to

detect drifts or abrupt shifts in the sensors' responses and to determine revisions to the flight coefficients. Validation studies of the resulting CERES data products will be used to verify sensor response changes, indicated by in-flight calibrations. The CERES science team will conduct detailed analyses of the first 6 months of in-flight calibrations and the validations before the sensor gains or offsets are revised. The flight coefficients (gains or offsets) will be revised only if a sensor response changes by more than 0.5% in the longwave region or 1% in the shortwave region.

After six months of CERES data are collected, the validation tests in Section 1.3 will be applied. At that point we should be able to statistically determine mean differences between the historical ERBS radiances and CERES radiances to approximately 1% in longwave and 2% in shortwave. The validation plan requires 6 months of in-flight calibration results before any sensors are revised. Thereafter, the empirical validation tests will be applied to each month of data separately in an attempt to determine if the gains and offsets are changing with time.

1.4.1 Planned Field Activities and Studies

N/A

1.4.2 New EOS-Targeted Coordinated Field Campaigns

N/A

1.4.3 Needs for Other Satellite Data

N/A

1.4.4 Measurements Needs (in situ) at Calibration/Validation Sites: Land, Buoys, etc.

The ERBS and CERES will be tied to international radiometric standards to a high accuracy by ground and on-board calibration systems. The addition of in situ measurements will not improve the accuracies of the instrument data products.

1.4.5 Needs for Instrument Development (Simulator)

N/A.

1.4.6 Geometric Registration Site/Geolocation - The geolocation process uses spacecraft ephemeris and attitude, Earth rotation and geoid, and instrument pointing data to calculate the latitude and longitude of the measurement location with estimated errors of the order of 1 km at Nadir. A heuristic description of the process is given by Lee *et al.* (1996a). The actual procedures used to implement the geolocation process are provided by the EOSDIS Core System Project in the Science Data Production (ECS) Toolkit. The use of the Science Data Production (SDP) Toolkit for geolocation is mandatory for EOS instruments. This mandate should eliminate some potential problems associated with correlation of satellite data from different instruments on EOS platforms. Co-registration refers to pointing knowledge between the CERES sensor optical axis and the axes of visible and infrared imaging sensors such as the TRMM visible imaging radiometer sounder

(VIRS) and EOS AM platform Moderate-Resolution Imaging spectrometer (MODIS). The pointing knowledge for the CERES footprints will be checked using coastline crossings (Hoffmann *et al.* 1987).

End-to-end validation and accuracy assessment techniques for the geolocation process require detection and geolocation of independently geolocated Earth features for comparison. For CERES, as with its predecessor ERBE, a technique for detecting coastlines under certain conditions and comparing their geolocated position with coastline maps will be used (Hoffmann *et al.* 1987). At night, using longwave radiance measurements, the coastline crossings were used to verify the ERBE pointing knowledge with average geographical local errors less than 6 km from the Earth Radiation Budget Satellite orbital altitude of 610 km. A brief overview of the CERES geolocation validation technique follows.

The ERBE longwave channel displayed a characteristic signature when the detector scanned certain high thermal contrast scenes such as desert adjacent to ocean. A typical desert/ocean coastline signature for the longwave channel is illustrated in Fig. 5. While the ocean maintains a relatively constant diurnal temperature, the desert temperature fluctuates resulting in a diurnal reversal in the slope of the coastline signature. A set of threshold values based on empirical data were applied to the absolute signal levels to filter out cloudy scenes. To limit the amount of data searched, only data predicted to be within 25 km of the coastline was used. A cubic equation was found to fit the signature well and the inflection point was assumed to represent the exact location of the coastline. The latitude and longitude of the inflection point was determined by interpolating from the adjacent measurements. An example of the Baja, California [22 - 32 North latitude, 243-252 East longitude] coastline points measured in this way and located on a map of the coastline is shown in Fig. 6. In ERBE geolocation studies, the coastlines of Australia [16-22 South latitude, 115-124 East longitude], Libya [30-33 North latitude, 14-23 east longitude], and the Arabian Peninsula [16-24 North latitude, 52-61 East longitude] have been used as validation targets, as well as the Baja coastline.

After the latitude and longitude errors are determined by comparison with the coastline map, the errors were transformed into cross track and along track errors for correlation with possible error sources. Additive cross-track and along-track bias parameters were introduced and adjusted to minimize the squared error. The bias parameters were determined for all cloud free coastlines under consideration over an extended time and displayed on a scatterplot to determine long term along-track and cross-track biases. An example of a typical scatterplot for a month is shown in Fig. 7.

Two conclusions drawn from coastline validation analysis for ERBE are that the geolocation process used was sufficiently accurate to accomplish the ERBE mission science objectives and that the coastline detection technique was sufficient for validating the geolocation process and evaluating long term end-to-end cross-track and along-track biases.

Enhancing the coastline detection technique for validating CERES geolocation processing will involve a few modifications to existing ERBE algorithms with potential for improvement. Most of the improvements are expected to be derived from utilization of CERES data products and SDP Toolkit routines that were not available during the ERBE mission, and bi-directional instrument scanning.

For the ERBE geolocation analyses, the shortwave channel was not used for coastline validation since it is sensitive to large variations due to clouds and was not useful at night. By analyzing VIRS and MODIS imager data, the CERES Science Team will determine the presence or absence of clouds in the field of view of the CERES detectors. This determination for all footprints is called a cloud mask. The cloud mask will be used to insure that a chosen coastline is cloud free so coastline analysis can be performed. The ability to filter out cloudy scenes from consideration may also allow use of the shortwave channel on appropriate daytime scenes.

The viewing angles for the ERBE coastline detection processing were limited to 30 degrees from nadir to reduce the effect of atmospheric refraction. The SDP toolkit allows the use of an atmospheric refraction model so these effects can be easily accounted for resulting in both increased accuracy and range over which coastline data can be analyzed.

Since the CERES instrument performs a bidirectional scan there will be an opportunity to assess biases inherent in the technique due to scan direction, i.e. scanning from ocean to desert vs. desert to ocean. The instrument also uses a biaxial scanning mode to acquire data for deriving angular direction models. Data obtained in the biaxial mode will scan a coastline from many different directions during a single pass. Data of this type may further enhance the potential for recovering biases due to scan direction or allow refinement of the cubic model used to define the detected coastline point.

1.4.7 Intercomparison Consistency (Multi-Instruments) Checks

1.4.7.1 - Single spacecraft - The single spacecraft sensor consistency checks involve inter-comparisons of (1) the three sensors' filtered Earth radiance measurements in the same instrument package (TRMM and EOS platforms) and of (2) the filtered Earth radiance output signals from the same type of sensor in two different instrument packages (EOS platform). Differences in the Earth radiance measurements will define the level of consistency. Angular distribution models (ADM) will not be used to account for the non-uniformity (anisotropy) of the target radiation fields.

The first intercomparison check was used in evaluating the consistency of the three Earth Radiation Budget Satellite scanning thermistor bolometer sensors. The evaluation approach is described in Section 1.3.3.3 and by Green and Avis (1996). For a particular geophysical scene like a desert, regional of a ocean, land region, overcast cloud scene, etc., or the combination of all the scenes, the ratios of any two sensor outputs should be constant with time if the sensors' responses do not drift or shift. If changes in the ratios are observed, then, more detailed reviews of the calibration time series should be evaluated to determine the size and direction of possible response drifts or shifts in one or both of the ratioed sensors. In the consistency check, the ratios of sensor outputs will be monitored for all scenes. If changes in the ratios occur, then ratios will be collected and evaluated for different spectral scenes (overcast clouds, oceans, deserts, land, etc.) into to determine the spectral nature of the sensor changes.

In the second consistency check, on each EOS platforms, the stabilities of the same type of sensors can be evaluated. Operating both EOS instruments in the cross-track scan mode, many

intercomparisons of the two shortwave, or total-wave, or window sensors Earth radiance measurements from the same geographical scene can be obtained. If both instruments are scanning in phase within ± 0.1 second, 2 pairs of intercomparison radiance measurements for each type of sensor and for every scan elevation position will be obtained every 6.6-second scan. Operating one instrument package in the cross-track scan mode and the other instrument in the rotating azimuth plane scan mode, 2 intercomparison radiance measurements from large (100 km) uniform scenes can be obtained at the nadir during a 6.6-second scan. At non-nadir elevation scan angles, the radiance intercomparisons cannot be conducted at the radiance level because the emitted and reflected Earth radiation fields vary with the azimuth angle outside of the cross-track plane. For the non-nadir elevation angles, no intercomparisons will be conducted because angular distribution models (Green and Hinton, 1996) are required to account for the anisotropy of the target radiation fields and to convert the Earth radiances into unfiltered Earth irradiances.

1.4.7.2 - Multi-spacecraft - Using multi-spacecraft platform CERES instruments (TRMM and EOS AM-1, or TRMM and EOS PM-1, or EOS AM-1 and EOS PM-1), filtered radiance products will be compared for the same type of sensor (shortwave, or total-wave, or window) in order to determine the consistencies among data products from the different CERES instrument packages. At least four times a day, at the intersection point between the two spacecraft ground tracks, the sensors from both platforms should measure nadir Earth radiances from the intersection point within 30 minutes. In Fig. 8, the intersection point measurements from two different spacecraft platforms are illustrated. Two intersection points are night and the other two occur during the day. Since radiances are independent of the detector solid angle, then, the measurements from the two different platforms can be compared without correcting for the differences in attitude. No comparisons of radiance products at non-nadir scan elevation angles will be performed because angular distribution models are required to account for the anisotropy in the Earth emitted and reflected radiation fields.

The EOS AM and PM platforms will have two identical CERES scanners that will be validated against each other (Section 1.4.7.1). In addition, each scanner will be used independently to establish the radiance statistics for earth validation target. We will then use one as the standard and test for significant gain and offset changes between the two as in Section 1.3.3.1 and 1.3.3.2.

1.4.8 Zero-radiance Offset Determination/Calibration Attitude Maneuver (CAM)

The flight sensor zero-radiance offset will be determined from observations of cold space [3K temperature radiance source (Turner 1993)], located between the Earth horizon and the spacecraft platform. The offset variations with elevation angle will be determined in ground laboratory facilities. In-flight, the offset variations will be determined again from observations of the nighttime side of the Earth (shortwave sensors) and of cold space (all sensors). The nighttime Earth shortwave radiance is zero by definition. During each orbit, the nighttime Earth radiances for each shortwave sensor is used to define the sensor zero-radiance offsets as a function of elevation angle. During the next series of day side measurements, these offset determinations are used to adjust the cold space determined offsets as a function of elevation angle. In the case of the total-wave and window sensors, the variations of the offsets with elevation angle will be derived from measurements of space during the 180° deep space spacecraft pitch/calibration attitude maneuver (CAM). For the Tropical Rainfall Measuring

Mission (TRMM) spacecraft experiment, the CAM will be conducted shortly after launch and thereafter annually. The frequency of each EOS platform CAM will be defined in the near future.

In Fig. 9, the TRMM CAM orbital geometry is illustrated in which the spacecraft is placed in an inertially-fixed configuration in which the spacecraft Earth Nadir pointing axis is maintained 180 degrees away from the spacecraft-Sun direction. The CAM orbital geometry should permit [1] deep space to be observed for about 20 minutes; and [2] deep space to be observed at geometries in which Earth radiance measurements are conducted [in the hemisphere centered around the nominal spacecraft Nadir direction]. The TRMM CAM geometry provides the best thermal environment in which to determine zero-radiance sensor offsets. It should be noted that the moon cannot be used as a radiance target because the CERES radiometers corresponding signals would be in the radiometers noise and close to the zero-radiance levels of the deep space background.

The CERES instrument radiometric offsets, corresponding to a zero radiance source, are determined every 6.6 seconds measuring the radiances of cold space at viewing geometries between the spacecraft and the Earth's limb. These offsets are applied to Earth-viewing measurement geometries in which the radiances from the Earth can be sensed. For the typical Earth scene of 240 W/m², the level 1 instrument offsets may vary as much as 1% with measurement geometry. CAM radiometric observations of space will allow the uncertainty associated with the measurement geometry to decrease to 0.2%.

There are no known engineering risks associated with CAM's. The CERES LaRC Project and Science Team have considerable experience in applying CAM deep space radiometric measurements in the level 1 data processing algorithms.

The sensor offsets can also be determined from comparisons with different spacecraft calibrated/validation radiance measurements of the same geographical scenes using the techniques of Avis *et al.* (1994).

1.5 IMPLEMENTATION OF VALIDATION RESULTS IN DATA PRODUCTION

1.5.1 Approach (Include Long-Term Calibration considerations)

The most important problem with implementing the empirical validation results as outlined in this section is to decide on the absolute standard. Most of the discussion here has been on validating one set of data against another. The purpose of ground based and in-flight calibration is to tie the satellite measured radiances to an international standard. However, from experience we know that instruments change in space and that in-flight calibration methods have their own set of problems. Thus, when two sets of satellite data show statistically significant differences, how do we decide which is correct or best? The answer will lie in examining all validation test from the various systems and searching for adjustments (be they zero) that give the most consistency and best explain the observations.

Although the validation tests in this section say little about accuracy to an international standard, they say much about precision and long-term stability. Using earth validation targets, we

would expect to detect instrument drift changes in the order of 0.1% (Green and Avis 1996).

1.5.2 Role of EOSDIS

Operational EOSDIS level 1 radiance data products will be used as source data for the validation studies, performed off-line, using science computing facilities (SCF).

1.5.3 Plans for Archival of Validation Data

The CERES in-flight calibration systems data will be stored in the world-wide web home pages and in the CERES science computing facilities. Results and summaries of the in-flight calibration and geolocation studies will be forwarded for publication in referenceable reports.

1.6 SUMMARY

This geolocation and calibrate validation plan is designed to verify the accuracies of the CERES unfiltered shortwave (0.3 μm - 5.0 μm) and longwave (5 μm - >100 μm) radiances; and the geographically locations of the target scenes. CERES in-flight calibration systems will be used to trace the transfer of a temperature-based absolute radiometric scale from the ground calibration facilities into orbit. The reliabilities of the CERES in-flight systems' technologies were demonstrated during the 1984-1990 ERBE spacecraft missions. The ERBE in-flight calibration systems verified the precisions of the ERBE radiance measurements at the levels approaching $\pm 0.3 \text{ Wm}^{-2}\text{sr}^{-1}$.

The geophysical locations of CERES radiance measurement footprints will be calculated with an estimated uncertainty of approximately 1 km, based upon the ground alignment measurements of the CERES instrument and spacecraft coordinate system axes as well as upon the ephemeris of the spacecraft. ERBE geometric registration sites will be used to determine the upper error limits in the scene position calculations. ERBE geolocation approach and sites verified the geographical positions of the radiance target scenes at uncertainty levels approaching 5 km.

On January 26, 1996, the CERES Proto-Flight Model (PFM) sensor package was mounted to the TRMM spacecraft. January 1997, the CERES Flight Model 1 (FM1) and Flight Model 2 (FM2) packages will be delivered for integration on the EOS AM-1 spacecraft platform.

Assuming no knowledge of the instrument, we have attempted to understand the instrument from examining the data. In a sense we have let the data speak for itself. This approach will give an added dimension to the instrument on-board validation.

The use of earth validation targets to validate one set of satellite data against another has been used extensively in this section. Consistency has been the rule most followed and is certainly a large part of validation.

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Table 1 CERES Instrument Accuracy Requirements (1 Sigma)

Detector	Shortwave		Total		Window
Spectral Region	0.3 \rightarrow < 5.0 μm		0.3 \rightarrow > 100 μm		8 \rightarrow 12 μm
Scene Levels	Less < 100 $\text{Wm}^{-2}\text{sr}^{-1}$	Greater > 100 $\text{Wm}^{-2}\text{sr}^{-1}$	Less < 100 $\text{Wm}^{-2}\text{sr}^{-1}$	Greater > 100 $\text{Wm}^{-2}\text{sr}^{-1}$	All Levels
Accuracy Requirements	0.8 $\text{Wm}^{-2}\text{sr}^{-1}$	1.0%	0.6 $\text{Wm}^{-2}\text{sr}^{-1}$	0.5%	0.3 $\text{Wm}^{-2}\text{sr}^{-1}$

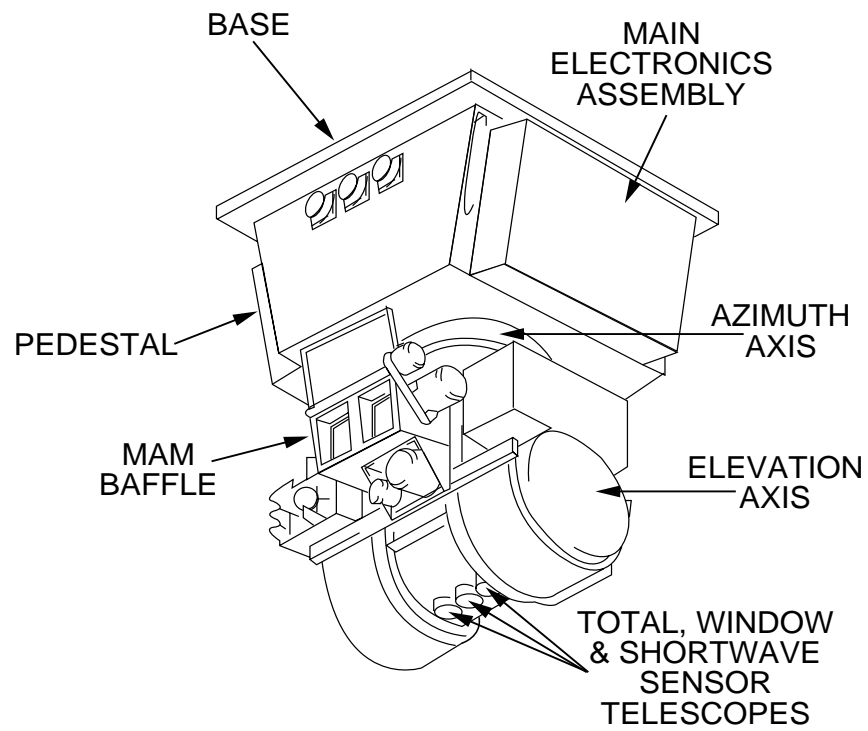


Fig. 1. CERES scanning sensor package

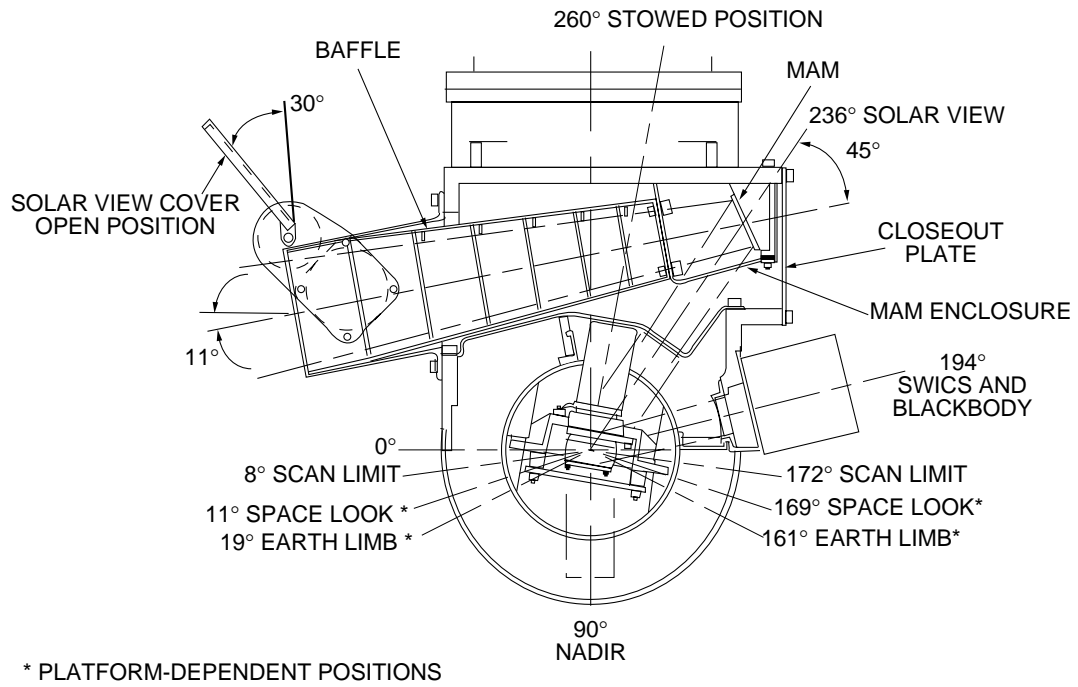


Fig. 2. CERES sensors elevation plane scanning geometry and flight calibration.

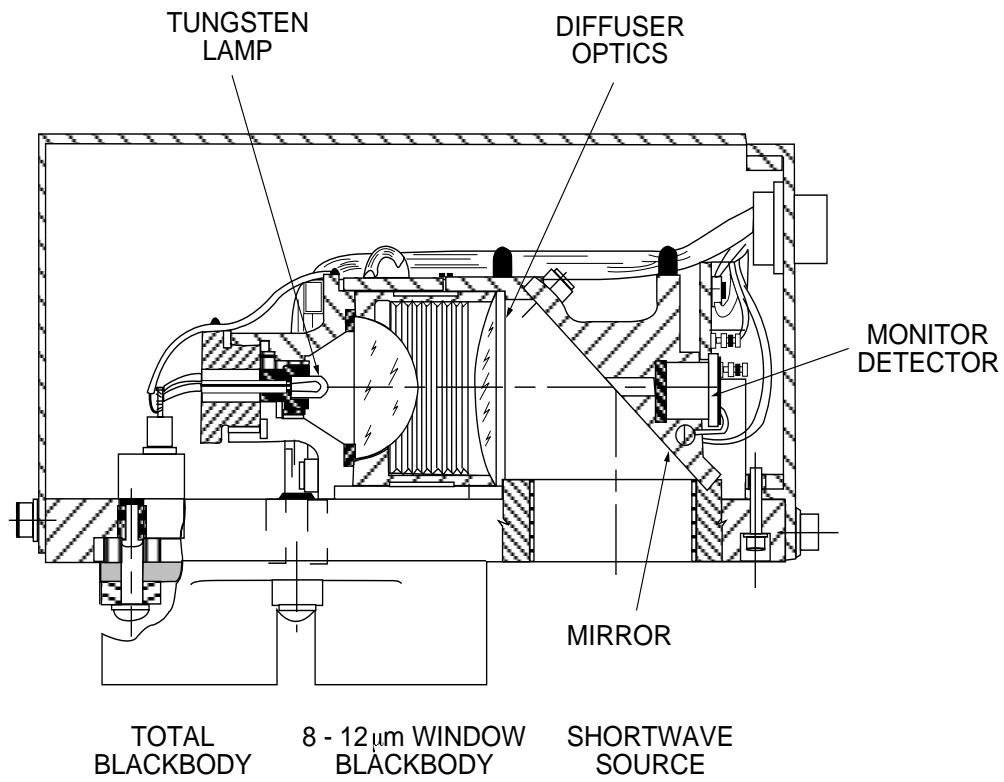


Fig. 3. Internal calibration module(ICM)

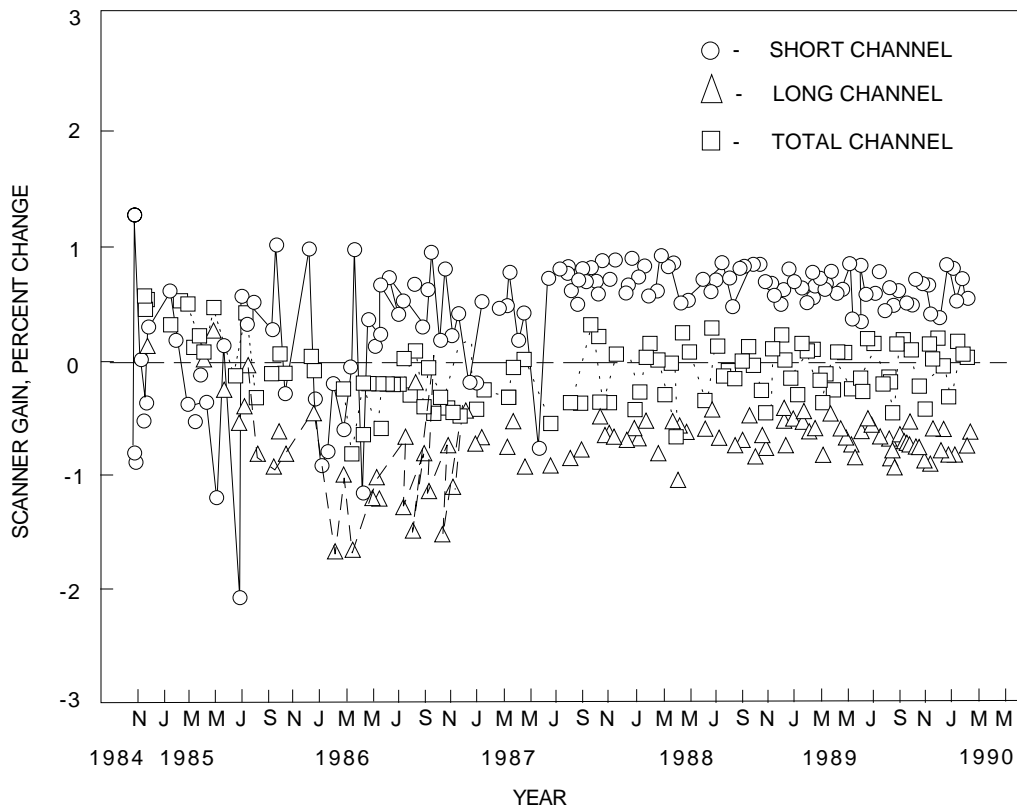


Fig. 4. ERBS thermistor bolometer flight calibration using the ICM.

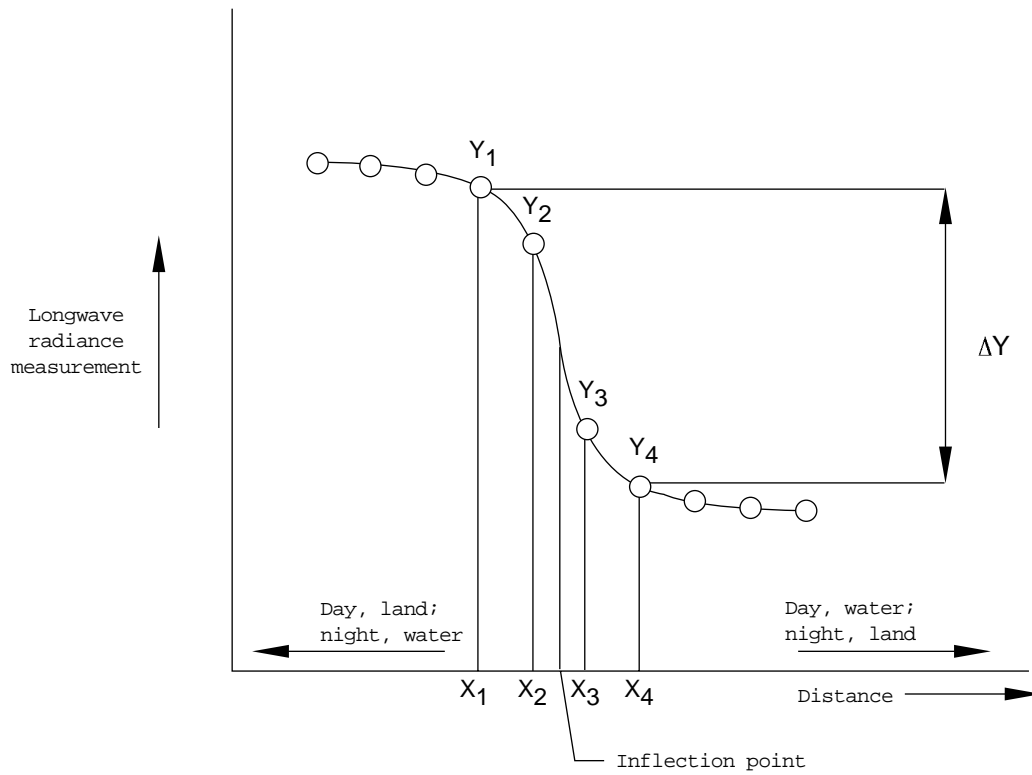


Fig. 5. Sketch of a typical ERBE longwave signal transition obtained when scanning normal to a coastline. The slope of the transition exhibits a diurnal variation. The inflection point was used to represent the location of the coastline.

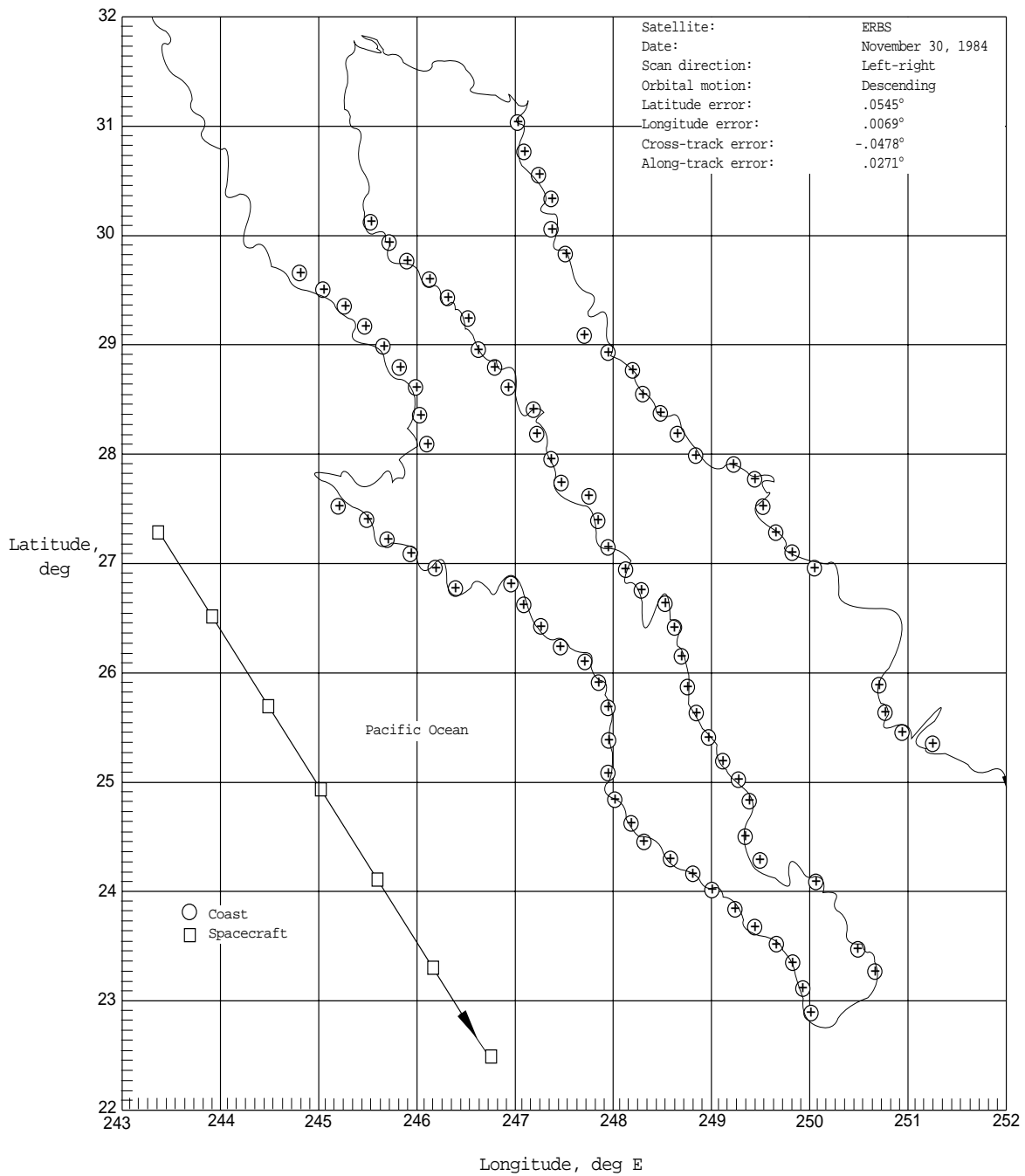


Fig. 6. Plot of the Baja, California coastline overlaid with measured locations of detected coastlines. The ERBS spacecraft sub-satellite point is also indicated in the lower left portion of the plot.

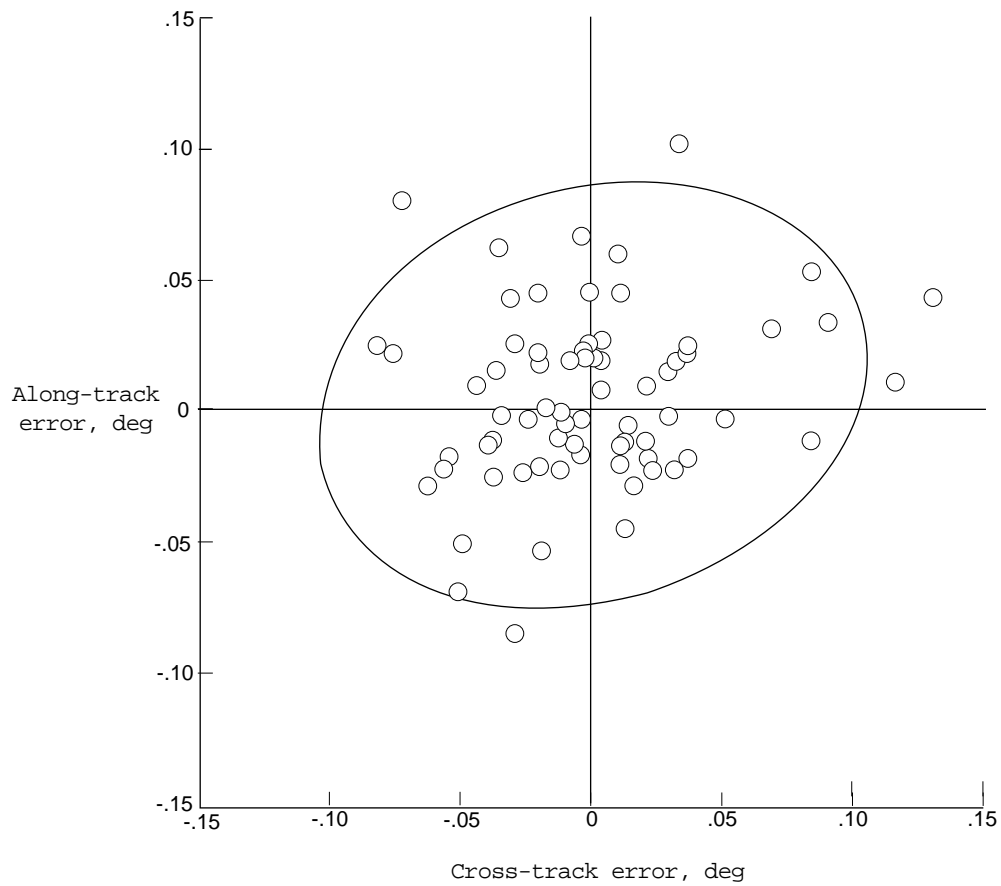


Fig. 7. Typical scatter-plot of an ensemble of along-track and cross-track bias errors for one month. Each point represents the average error calculated for a single coastal region.

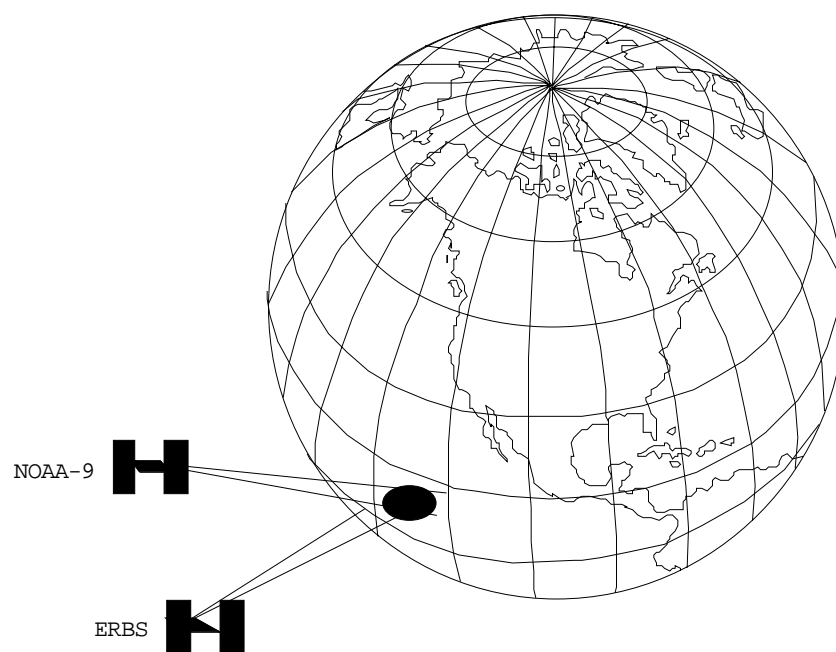


Fig. 8.

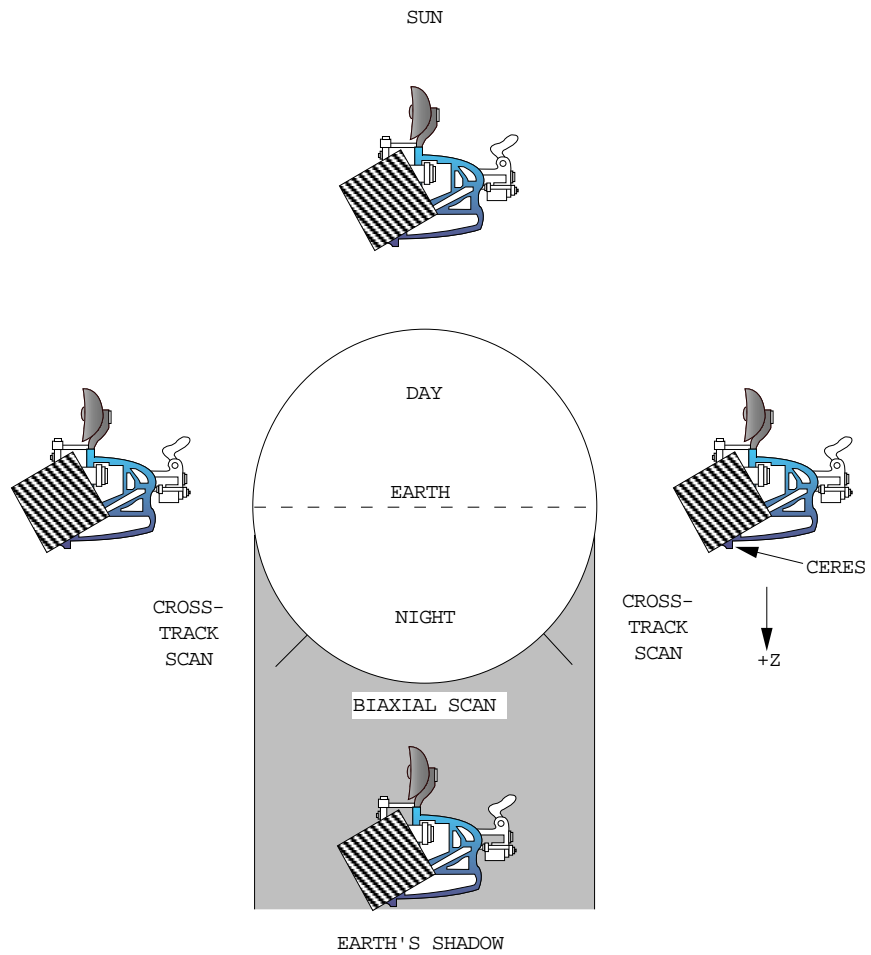


Fig. 9.

CERES VALIDATION SUMMARY

Subsystem 1.0 - CERES Geolocate and Calibrate Earth Radiances

Data Products

- **Earth radiances:**
 - 1) **Filtered broadband shortwave [0.3 - 5.0 μ m]**
 - 2) **Total-wave [0.3 - $>100 \mu$ m]**
 - 3) **Water vapor window [8 - 12 μ m]**

Approach

- **Resolution/geometric sites used during the ERBE spacecraft missions**
- **Radiometric accuracy and precision in-flight calibration systems [demonstrated by ERBE] measurement accuracy via ground-to-orbit and precision via in-flight time series**
- **Radiometric precision/consistency checks among same and different types of CERES sensors using ERBE techniques**
- **Compare CERES radiances to earth validation targets calibrated with 5 years of ERBS data**
- **Three channel redundancy check for consistency**
- **Offsets validated using spacecraft pitch-up and monitored monthly against ERBS global limb-darkening**

CERES VALIDATION SUMMARY

(CONTINUED)

Validation Activities

- **Prelaunch**

- 1) All validation and consistency checks will be based upon CERES sensor ground calibration data sets
- 2) Establish radiation statistics of earth validation targets. Longwave target is tropical ocean at night. Shortwave target is desert region in daytime. Learn technique by applying to ERBE NOAA-9 data.

- **Postlaunch**

- 1) Collection of in-flight calibration measurements and calculated filtered Earth radiances on designated calibration days
- 2) Compare CERES radiances to historical ERBS radiances via earth validation targets.

Archive

- In-flight calibrations will be archived in BDS format at EOSDIS
- Publications describing the sensor calibration and validation results as well as public science computing facility (SCF) files of the appropriate calibration and validation data.